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Microstereolithography: a Review

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ABSTRACT

Microstereolithography is a technology at the interface of the microengineering and rapid prototyping domains. It has evolved from the stereolithography technique, and is also based on a light-induced layer-stacking manufacturing. As the resolution of the microstereolithography technique is far better than the one of rapid prototyping technologies, this technique is of particular interest in the microengineering domain where its 3D capability allows the production of components no other microfabrication technique can create.

The first developments of the microstereolithography technique have started in 1993 and different research teams have developed machines since, using different approaches. This paper reviews the major microstereolithography processes developed until now.

Microstereolithography is starting to be a commercially available manufacturing process. As the market for miniaturized products grows rapidly, there is an increasing need for high-resolution small size prototype parts. If the production of small mechanical components is the first commercial application of microstereolithography, this technology can also produce useful components for the microrobotic, microfluidic, microsystems and biomedical fields. Current research in the microstereolithography field is focused on using ceramic composites as material to manufacture complex three-dimensional parts that can be sintered to produce pure alumina microcomponents.

INTRODUCTION

Microstereolithography is the general designation of various microfabrication technologies based on the principle used in stereolithography, a rapid prototyping technology patented in 1984[1,2] and used in the automotive and aerospace industries as well as in all industrial and technological fields requiring the manufacturing of three dimensional prototype parts. If the word "Microstereolithography" is now commonly accepted by almost every user and developer of this technology, many different names (micro-photoforming, IH process, spatial forming, 3D optical modeling, microstereophotolithography, optical forming, etc...) have been used by the research teams who published the first reports on this technique, corresponding to variations in the design of the built apparatuses. Nevertheless, whatever their name can be, all microstereolithography machines have the same aim and the same basic principle: They allow to build small-size, high-resolution three-dimensional objects, by superimposing a certain number of layers obtained by a light-induced and space-resolved polymerization of a liquid resin into a solid polymer.

IMPROVEMENT OF THE STEREOLITHOGRAPHY RESOLUTION

To understand how stereolithography, a rapid prototyping technology with a 150µm resolution, could evolve towards microfabrication, a quick recall on its principle and on the photo-polymerization mechanism will show the possible paths that have been followed by the different research teams working in this field.

Of course, many factors (machine-, software-, process-, resin-related, etc..) affect the resolution of the stereolithography parts. The aim of this section is not to inventory all of them, but to define the principal directions that can lead to an important improvement of the resolution and which can be the starting point in the creation of high-resolution stereolithography processes for manufacture of small-sized parts.

Stereolithography

The stereolithography process is the first and most widely used rapid prototyping technique. It allows to build a part layer by layer by laser induced polymerization. The laser beam is focused and scanned on the open surface of the photosensitive liquid and a liquid/solid transformation occurs locally, which allows to create the shape of one layer of the object. When a layer is finished, fresh resin is spread on top of the already manufactured part of the object, and the light-induced solidification of the next layer is started.

Photopolymerization

Photopolymerization is the chemical reaction underlying the change of state that makes it possible to create the layers composing the objects in the stereolithography process: the absorption of a given quantity of photons per volume unit of photosensitive medium creates reactive species, which induces the polymerization of the liquid monomer into a solid polymer by a chain reaction. This polymer is generally cross-linked and cannot dissolve again in a monomer bath.

The evolution of the polymerized depth with the irradiation time in stereolithography can be easily predicted and is presented extensively in the literature [3,4]. Equation 1 gives the temporal evolution of the polymerized depth e:

$$e = \frac{1}{\alpha c} Ln\left(\frac{t}{t_0}\right) \qquad (1)$$

where t (s) is the irradiation time, t_0 (s) the irradiation time at the threshold, α (l.mol^{-1}.cm^{-1}) the Napierian coefficient of molar extinction, c (mol.l^{-1}) the concentration of the absorbing substance. This relation shows that the evolution of the polymerized depth e with the irradiation time is logarithmic. This simple model is in good agreement with experimental results in the case of resins that do not undergo changes in their absorption coefficient during the polymerization process.

Reduction of the polymerized depth

To improve the resolution of the stereolithography process in the vertical direction, thinner layers have to be created. Making smaller layers mechanically by spreading a thinner layer of fresh resin on the surface of the object to be manufactured is not sufficient to control the vertical resolution. The most important parameter is the light penetration depth in the medium [4,5]: If it is not correctly controlled, the light could penetrate deep in the chemical medium and go through some already polymerized layers, which could result in a loss of resolution in the already polymerized part of the object. To control accurately the polymerization depth, different solution can be imagined:

a) Irradiating the resin in conditions close to the polymerization threshold

When the photosensitive chemical medium is irradiated during a short time so that the energy received by the resin is close to the critical energy E_c required to start the polymerization process, equation 1 can be simplified and written:

$$e \cong \frac{1}{\alpha c}\frac{t-t_0}{t_0} \qquad (2)$$

Thin polymerized layers can be obtained and their thickness can be controlled by the choice of the irradiation time, but as the incident energy received by the resin is close to the critical energy required to start the polymerization phenomenon, they have in general poor mechanical properties. Moreover, a small variation of the irradiation energy leads to important changes in the polymerized depth, which is not compatible with vector-by-vector fabrication processes. In particular, when two polymerized vectors are secant, the intersection point is irradiated with twice the energy of other points, which makes it impossible to control accurately the polymerized depth (figure. 1).

b) Using a highly absorbing chemical medium

When the irradiation energy is significant compared to the critical energy, equation 1 can be written:

$$e \cong \frac{R_1}{\alpha c} \quad \text{where} \quad R_1 = Ln\left(\frac{t}{t_0}\right) \qquad (3)$$

There are only very small variations of R_1 with small variations of the irradiation time t, when $t >> t_0$. In this case, the polymerized thickness does not depend much on small variations of the irradiation time, which is better adapted to vector-by-vector fabrication. The polymerized thickness can be reduced by using reactive resins with low value of the optical thickness $\mu=1/\alpha c$. Such resins show a strong absorption of the irradiation wavelength and can be obtained by formulating chemical media containing high concentrations of highly absorbing chemicals (initiators or non-reactive chemicals).

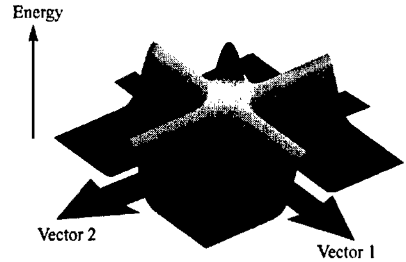


Figure 1. When two polymerized vectors are secant, the intersection point receives a double energetic dose. When the irradiation energy is close to the critical energy, this leads to significant changes in the polymerized thickness.

Improving the transverse resolution of stereolithography

The horizontal resolution of the stereolithography process is mainly a function of the resolution of the scanning system and quality and stability of the laser beam. The laser diameter on a standard SLA-250, the most widespread commercial stereolithography machine commercialized by the company 3D Systems, (0.25 mm) sets a lower limit to the resolution and feasibility of small size features. Given a stable laser beam profile, accurate correction factors for the width of the scanning beam and resin shrinkage, a horizontal precision in the order of the half of the laser beam width, as a rule of thumb, can be routinely achieved.

A significant improvement in the horizontal resolution can be achieved by using a single mode instead of the common multimode HeCd laser on a conventional SLA-250 machine. The spot size at the focal point can be reduced from 0.25mm to about 0.08-0.1mm, which pushes down the lower limit of feature feasibility [6]. This technique has found applications in the area of watch making, electronics [7] and in the electro- and medico-technical industry (hearing aids). A few specialized service bureaus worldwide commercially produce small size high-resolution prototypes made with the small spot stereolithography technology.

Further improvements of the horizontal resolution of the stereolithography process requires the reduction of the interaction volume between light and matter. This leads to different microstereolithography concepts that will be discussed in the next paragraph.

MICROSTEREOLITHOGRAPHY: CONCEPTS AND PROCESSES

Vector-by-vector microstereolithography

The basic principle of all vector-by-vector microstereolithography machines is very similar to the one of the stereolithography technique: every layer of the object is made by scanning a focused light beam on the surface of a photosensitive resin. To get a better resolution than stereolithography, the beam is focused more precisely in order to reduce the spot size to a few micrometers in diameter, which requires additional technological developments in the designed microstereolithography machines. In particular it is necessary to measure precisely and continuously the position of the surface on which the beam is scanned and to dynamically focus it with a sufficient precision. A first kind of microstereolithography processes based on this principle has been developed, and the vector by vector scanning of every layer is in general not realized with scanning mirrors but by moving the photoreactor with x-y translation stages.

a) Constrained surface technique

The first papers published at an international conference on microstereolithography were issued in 1993, one at the MHS conference by Takagi et al. [8] and a second at the MEMS conference by Ikuta et al. [9]. The processes that are described in those papers and which are more extensively presented later in other publications, are relatively similar. They are based on a vector by vector tracing of every layer of the object with a light beam, focused on the reactive resin through a transparent window. In this variation of the microstereolithography process, the point on which the light beam is focused remains fixed, but x-y translation stages are used to move either all the optical system focusing the light beam on the resin surface, or the photoreactor in which the object is made. A shutter occults the light during translation without polymerization or when a new layer is made (Figure 2a).

The use of a glass window to push on the liquid and obtain a layer of constant thickness avoids the problem related to spreading the fresh resin on the already polymerized part of the object. However, polymerizing through a transparent window has a major disadvantage: the formed polymer sticks to it, which can result in partial or total destruction of the part during the manufacturing process.

Apparatus described by:	Takagi et al. (1993)	Ikuta et al. (1993)
Name of process	Photo forming	IH process
Light source	He-Cd laser, UV (325 nm)	Xenon lamp, UV
Constrained surface with	Quartz window +PFA tape	Transparent window
Irradiation	From bottom	From top
Maximum size of structure	20x20x20mm	10x10x10mm
Announced resolution	5 x 5 x 3 μm (x,y,z)	60μm, up to 8μm
Resin type	Acrylic	Not specified

Table I. Characteristics of vector-by-vector microstereolithography machines operating with the constrained surface technique, described by Takagi and Ikuta in 1993.

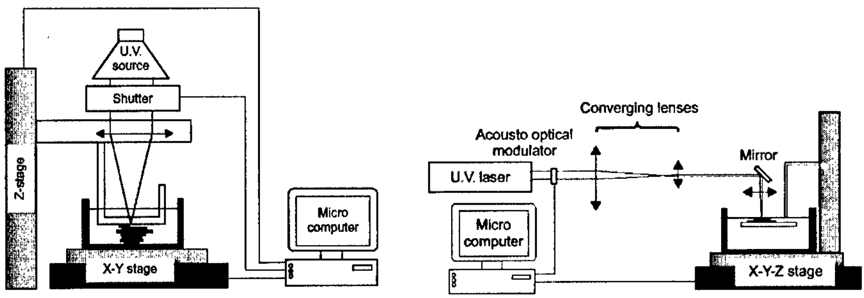
b) Free surface technique

To avoid the adhesion of the polymer to the transparent window in the constrained surface processes, some research teams developed vector-by vector microstereolithography processes based on a free surface technique (Figure 2b). These processes are very similar to the ones presented in the previous paragraph, except the surface of the liquid resin is not constrained by a transparent window. The main disadvantage of this method is the difficulty in controlling the thickness of the deposited liquid layer: Once the liquid layer is spread on the surface, it is necessary to wait for the gravity forces to level the surface. The time required to obtain a horizontal fresh layer of resin depends on the rheological properties of the resin. Low viscosity monomers have to be used as often as possible.

Zissi et al. published a first paper describing a vector-by-vector microstereolithography process using the free surface technique in 1994 [10], and another was presented in 1998[11] by Zhang et al.

Apparatus described by:	Zissi et al. (1994)	Zhang et al. (1998)
Name of process	Microstereophotolithography	Micro-stereolithography
Light source	Argon ion laser	Argon ion laser
Surface monitoring	IR laser diode	CCD camera
Announced resolution	30 x 30 x 20 μm (x,y,z)	Spot has 1-2 μm
Resin type	Acrylate based resin containing non-reactive absorbers and polymerization inhibitors	HDDA monomer containing 4wt% of benzoin ethly ether as photoinitiator

Table II. Characteristics of the vector-by-vector microstereolithography machines operating with the free surface technique, described by Zissi and Zhang.



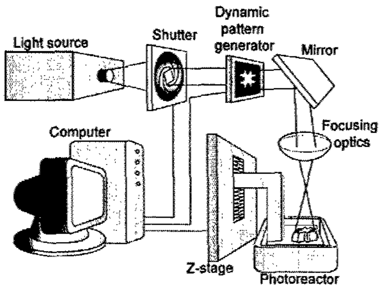
(a) Constrained surface technique *(b) Free surface technique*

Figure 2. Schematic diagram of vector by vector microstereolithography processes (from [12]).

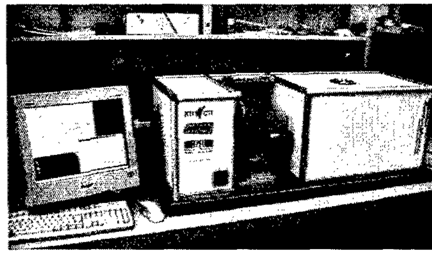
Integral microstereolithography

Integral microstereolithography has started to be studied more recently than vector-by-vector microstereolithography because integral processes are much more different from conventional rapid prototyping techniques than vector-by-vector processes. Moreover, the components that could be used as dynamic pattern-generators, which are the key components in integral processes, were not commercially available with a sufficient resolution until 1995.

In integral microstereolithography, every layer of the object is made in one irradiation step by projecting its image on the surface of the photopolymerizable resin, with a high resolution an a certain depth of focus. This avoids the problems related to the fine focusing of a light beam in one point on the liquid surface, which is often limiting vector-by-vector microstereolithography processes. A pattern generator allows to shape the light, such that it contains the image of the layer to be solidified. This image is then reduced and focused on the surface of the reactive medium with the appropriate optical system. The superimposition of the different layers composing the object is done in the same way as in conventional stereolithography (Figure 3a). Integral microstereolithography processes are fast, because the irradiation of an entire layer is done in one step, whatever its pattern may be.



(a) Principle



(b) DMD™ based machine at EPFL

Figure 3. Integral microstereolithography.

a) Liquid crystal displays (LCDs) as pattern generators

The first paper presenting an integral microstereolithography machine was published in 1995 by Bertsch et al. [13] and the component used as dynamic pattern generator was a LCD panel developed for rear projection applications. Every pixel of such LCD panels is a small cell that can be set either to its transparent state or to its opaque state, by changing the orientation of the molecules it contains. By inserting a liquid crystal display on the optical path of the light beam, the transmitted light can be modulated, which allows to use successfully those LCD screens to manufacture complex in shape objects by microstereolithography [12].

When the first experiments were started on the use of LCDs as spatial light modulators in microstereolithography, this component was not compatible with UV light. A visible light source was required in the apparatus and a photopolymerizable resin reacting with visible wavelengths had to be developed.

In 1998, Loubère at al. [14] presented another integral microstereolithography process using a LCD display as pattern generator and performing the resin irradiation with visible wavelengths. Chatwin et al. [15] presented in 1998 an integral microstereolithography process operating in the UV that uses a special LCD display, transparent to wavelength above 350nm. It is a polysilicon thin film twisted nematic liquid crystal display manufactured by CRL Smectic Technologies Ltd.

Apparatus described by:	Bertsch et al. (1995)	Chatwin et al. (1998)	Loubère et al. (1998)
Light source	Ar+ laser (515nm)	Ar+ laser (351.1nm)	Halogen lamp
LCD display resolution	260x260 pixels	600x800 pixels	640x480 pixels
Speed	90 layers per hour	< 60 layers per hour	60 layers per hour
Announced resolution	5 x 5 x 5 µm (x,y,z)	? x ? x 50µm (x,y,z)	5 x 5 x 10 µm (x,y,z)
Resin	PETIA with EosinY as photo-sensitiser and amine as co-initiator	Cibatool 5180 (low viscosity epoxy-based resin)	PETIA with EosinY as photo-sensitiser and amine as co-initiator

Table III. Characteristics of the integral microstereolithography machines described by Bertsch, Chatwin and Loubère.

b) Digital Micromirror Device™ as pattern generator

The Digital Micromirror Device (DMD™) produced by Texas Instruments, which is an array of micromirrors actuated by electrostatic forces can also be successfully used as pattern generator for microstereolithography. This component is a microelecromechanical system working as a light switch [16].

The DMD™ is monolithically fabricated by CMOS-like processes over a CMOS memory, and is made of 16 μm square aluminum mirrors that can reflect the light in one of two directions, depending on the state of the underlying memory cell. The rotation of the mirror is accomplished through electrostatic attraction. By combining the DMD™ with a suitable light source and optical system, each mirror reflects the incident light either into or out of the pupil of the projection lens by a simple beam-steering technique. When the mirror is rotated to +10 degrees, the corresponding pixel in the image appears bright, whereas when the mirror is rotated to –10 degrees, the corresponding pixel appears dark.

To demonstrate the feasibility of the technology, an array of micromirrors having a VGA resolution (640 x 480) was used in a first prototype developed to work with visible wavelengths by Bertsch et al [3]. The typical manufacturing speed of this machine is of about 200 to 300 layers per hour, depending on the shape of the layers, and the resolution , up to $3x3x3\mu m^3$.

In a second microstereolithography machine created to operate in the UV, a DMD™ chip having a XGA (1024 x 768) resolution was used. This apparatus was developed at the Swiss Federal Institute of Technology in Lausanne, EPFL (figure 3b) for use in an industrial context. An acrylate-based resin has been formulated to be used with this apparatus. It is highly absorbing for the irradiation wavelengths and has mechanical properties close to the ones of conventional stereolithography resins.

Creating an object inside the reactive medium

There are of course many advantages to creating the object directly in the resin, without superimposing layers: No support parts are needed. No time is spent spreading the liquid on the part being manufactured, which potentially can speed-up the process significantly. Freely movable structures can be fabricated without the need of sacrificial layers. Many attempts have been done to develop such kind of processes in the rapid prototyping domain, for creating big objects, but they have never been successful. However, when making micro objects some solutions have been found to create them directly inside the reactive medium.

When objects are created by microstereolithography by polymerizing directly inside the reactive medium, the energetic density of the light beam has to be maximal under the surface, which requires adapted chemical media and complex optical systems. This approach allows to create very small objects because very small increments are possible in both the vertical and transverse direction.

a) Two-photon process

Two-photon absorption is an optical nonlinear phenomenon that occurs at sufficiently high level of irradiance in all materials, when the combined energy of two photons matches the transition energy between the ground state and the excited state. The rate of two-photon absorption is proportional to the square of the incident light intensity. The quadratic dependence of the two-photon absorption rate on the light intensity confines the absorption to the area at the focal point. As the two-photon transition rate is extremely small, the power of the light source has to be extremely high.

Maruo et al., who developed the first two-photon microstereolithography apparatus in 1996 [17], used a mode locked Ti:Sapphire laser emitting at 770nm. The beam power at peak in the resin was about 3kW with a repetition rate of 76 MHz and a pulse width of 130fs. The resin was transparent to IR light and did not attenuate the light beam, which could be focused inside the resin without polymerization at the surface. This process was the first microstereolithography process having a submicron resolution.

Kawata et al. developed a microstereolithography apparatus based on the same principle with a 120nm resolution, which is smaller than the diffraction limit (the nonlinear effects allow to exceed it). To demonstrate the very high resolution obtained with this process, Kawata et al. built a micro-bull, which is 10μm long and 7 μm high [18].

b) Single-photon process

In a single-photon under-surface manufacturing microstereolithography process, the nonlinearity of the photopolymerization reaction in response to the irradiation intensity is used. The presence of oxygen molecules dissolved in the resin inhibits the polymerization reaction. As a result, if the light intensity is adequately low, polymerization does not start. This phenomenon can be exploited to selectively solidify the resin by regulating the intensity of the light. A radiation that is weakly absorbed by the resin can be tightly focused inside the photoreactor under optimal conditions, such that the intensity is sufficient to solidify the resin near the focal point but not in the out-of-focus region.

Maruo et al. presented a microstereolithography process based on the single-photon under surface polymerization at the MEMS conference in 1998 [19]. The single photon photopolymerization is stimulated not by a pulsed laser but by a continuous wave blue He-Cd laser. As conventional UV-initiated resins weakly absorb the blue wavelength at 441.6nm, conditions in which the single photon process can be exploited exist. The process resolution is close to the one of the 2-photon technique: the best lateral and depth resolutions attained were 0.43 and 1.4 μm respectively.

APPLICATIONS OF MICROSTEREOLITHOGRAPHY

Microstereolithography is starting to be a commercially available manufacturing process. There is a growing need for high-resolution small size components in the rapid prototyping domain. As the market for miniaturized products grows rapidly, there is also an increasing need for high-resolution prototype parts. When small size objects have to be built with dimensions of only a few millimeters or less, current rapid prototyping technologies are limited with respect to the feasibility of small features: openings and small holes are difficult to make and have to be re-drilled once the prototype is built, which is particularly difficult. Another aspect, which has to be taken into consideration for small components, is that manual surface finishing can be a very tedious, if not impossible task.

The small-spot laser stereolithography technology is the first step towards high-resolution rapid prototyping, and this process is made commercially available by a few service bureaus around the world. The resolution obtained with this technology is sufficient for a large number of products; however, there are still many applications that demand substantially higher resolution and precision.

The first commercial application of microstereolithography is the production of components for rapid prototyping applications. The first company that started to sell such prototype parts is microTEC in Duisbourg, Germany [20]. Recently, Proform AG, in Marly, a Swiss service bureau already specialized in high-resolution prototype parts also started such activity. If the production of small mechanical components is the only current commercial application of microstereolithography, all universities and research institutes who investigated this technology manufactured interesting objects and tried to find potential applications for this process.

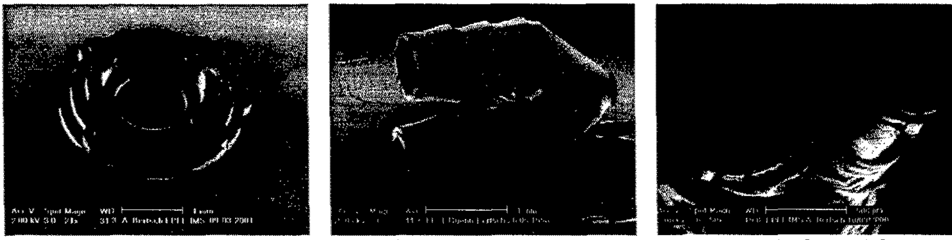
Objects with a geometric complexity

All research teams who realized microstereolithography machines tried to validate the concept they developed by manufacturing components that are difficult or impossible to build with conventional microfabrication processes, like bending pipes [9], micro coil springs [9], spiral structures [21], microgears of different shapes [11,12,22,23], freely movable microstructures [19,23], 3D networks, scale models [3,6], (small car, statue of liberty (figure 4c), micro turbines, Christmas tree) etc... Of course all these test objects have no real use, but they illustrate the wide diversity of shapes and the intricate details that can be produced with the microstereolithography processes.

Small mechanical components

The manufacturing of small size high-resolution components that rapid prototyping technologies are unable to create with adequate detail is of course the first domain in which microstereolithography could be successful (figure 4a). Most research teams have investigated more microsystem/microfluidic related uses of this technology, but have neglected to investigate thoroughly this field. There is a growing demand of high-resolution prototype objects in particular in the medico-technical industry. Medical probe heads in which optical and chemical sensors could be embedded will be less invasive if they could be created with a smaller size [6]. Hearing-aid manufacturers try to design lightweight products small enough not to be detected, comfortable, with rounded shapes to be close from the natural geometry of the ear canal. For such applications it is necessary to prototype small mechanical components with intricate details. In the medical domain, 3D models made by microstereolithography can also be used to train the surgeons before a very difficult operation (At the HARMST'01 workshop MicroTec presented a model of the ear canal that was used for this purpose).

In the electro-technical industry microstereolithography can be advantageously used for the prototyping of small connectors, and many other examples can be found in different domains.



(a) Prototype part *(b) Fludic connector* *(c) Scale model*

Figure 4. Objects made by microstereolithography.

Microsystem components

As microstereolithography has evolved from rapid prototyping technologies and does not yet allow a wafer-level manufacturing, different research teams have investigated its possible combination to conventional silicon-based micro-machining technologies in order to integrate new functions on planar structures and create original microsystem components. In this context, microstereolithography has been combined to thick-resist UV lithography to associate curved and conical structures with the smooth and vertical walls and micrometer accuracy of SU-8 technology [24]. It has been combined to piezoelectric elements [25] and shape memory alloy wires[26] to create actuators. Microstereolithography has also been used for prototyping MEMS components and optimizing their geometry, before investing in photomasks and using more conventional cleanroom technologies for mass production [27]. In the future, the manufacturing of hybrid polymer structures by combining various types of polymers, such as conductive polymers, polymers of various refractive index or flexible polymers could also lead to the creation of new optical, chemical and biochemical microsystems with the microstereolithography technology [28].

Microfluidic components

Many authors studied the possibility to create microfluidic components with the microstereolithography process. It is indeed relatively easy to create pipes and connectors having shapes that are impossible to be obtained by conventional microfabrication technologies with this technique (figure 4b). Different passive microfluidic components are presented in the literature: pipes, channels, connectors, mixers, etc. More complex passive microfluidic components have also been presented, obtained either by combining different technologies or by inserting membranes or films during the patterning process (a cell-free biochemical chip for Luciferase synthesis, a micro-osmotic valve prototype for insulin injection, a concentrator chip, etc...)

By combining structures made by microstereolithography with piezoelectric actuators or shape memory alloy components, active fluidic components can also be obtained (micropumps [29], switching valves, etc...) Once active and passive microfluidic components can be produced, their assembly can lead to complex fluidic systems. Ikuta et al. developed a simple method for holding and connecting fluidic components to obtain chemical and biochemical chips. This versatile fluidic device has been named "Biochemical IC"[30].

CONCLUSION - MICROSTEREOLITHOGRAPHY OF COMPOSITE MATERIALS

One of the major limitations of the microstereolithography technology is related to the materials that can be used in this manufacturing technique: Only a few polymers can be used, acrylates in general or eventually epoxies. Because of their three dimensional geometry, most objects produced by microstereolithography cannot be molded, which implies that, for some applications, microstereolithography is no longer a rapid prototyping technology but a manufacturing technique. In this case, the produced objects need to have adequate mechanical, chemical or physical characteristics. As a result, studies on the use of new materials for microstereolithography have been started, and in particular on the use of composite materials made of ceramic particles embedded in a polymer matrix as reactive medium in this technology. The ultimate aim is of course the production of micro-components in ceramic materials, which can be obtained by sintering the composite. However, for sintering successfully such composite components, the load of particles embedded in the resin has to be sufficiently high, which increases significantly the viscosity of the chemical media. If different teams have started to work in this field, no satisfactory solution has been obtained yet, but this research in the material domain are very promising for the utilization of microstereolithography not only as a prototyping technology but as a manufacturing technique.

REFERENCES

1. C. W. Hull, US Patent Patent No. 4,575,330 (1986).
2. J. C. André, A. Le Méhauté, and O. De Witte, French Patent Patent No. 84,11,241 (1984).
3. L. Beluze, A. Bertsch, and P. Renaud, presented at the SPIE Symposium on Design, Test and microfabrication of MEMs/MOEMs, Paris, France, 1999.
4. S. Zissi, A. Bertsch, J. Y. Jézéquel, S. Corbel, J. C. André, and D. J. Lougnot, Microsystem Technologies **2** (2), 97 (1996).
5. T. Nakamoto, K. Yamaguchi, P. A. Abraha, and K. Mishima, J. Micromech. Microeng. **6** (2), 240 (1996).
6. A. Bertsch, P. Bernhard, C. Vogt, and P. Renaud, Rapid Prototyping Journal **6** (4), 259 (2000).
7. P. Bernhard, Rapid prototyping report **Dec. 1997** (1997).
8. T. Takagi and N. Nakajima, presented at the 4th International Symposium on Micro Machine and Human Science (MHS'93), 1993.
9. K. Ikuta and K. Hirowatari, presented at the 6th IEEE Workshop on Micro Electro Mechanical Systems (MEMS'93), 1993.
10. S. Zissi, A. Bertsch, S. Ballandras, S. Corbel, J. Y. Jézéquel, C. Belin, D. J. Lougnot, and J. C. André, presented at the 3e Assises Européennes du Prototypage Rapide, Paris, France, 1994.
11. X. Zhang, X. N. Jiang, and C. Sun, Micro Electro Mechanical Systems (MEMS) ASME **66**, 3 (1998).
12. A. Bertsch, S. Zissi, J. Y. Jézéquel, S. Corbel, and J. C. André, Micro. Tech. **3** (2), 42 (1997).

13. A. Bertsch, S. Zissi, J. Y. Jézéquel, S. Corbel, and J. C. André, presented at the 4èmes assises européennes du prototypage rapide, Paris, France, 1995.
14. V. Loubère, S. Monneret, and S. Corbel, presented at the the 4th Japan-France Congress and 2nd Asia-Europe Congress on Mechatronics, Kitakyushu, Japan, 1998.
15. C. R. Chatwin, M. Farsari, S. Huang, M. I. Heywood, P. M. Birch, R. C. D. Young, and J. D. Richardson, Applied optics **37** (32), 7514 (1998).
16. L. J. Hornbeck, presented at the Electronic Imaging (EI'97) - Projection displays III, San Jose, California, USA, 1997.
17. S. Maruo, O. Nakamura, and S. Kawata, presented at the SPIE - Optics for Science and New Technology, 1996.
18. S. Kawata, H.-B. Sun, T. Tanaka, and K. Takada, Nature **412**, 697 (2001).
19. K. Ikuta, S. Maruo, and S. Kojima, presented at the 11th IEEE Workshop on Micro Electro Mechanical Systems (MEMS'98), Heidelberg, Germany, 1998.
20. H. Bohlmann and R. Götzen, presented at the 4th International Workshop on High Aspect Ratio Micro Structure Technology (HARMST'01), Baden-Baden, Germany, 2001.
21. S. Maruo, O. Nakamura, and S. Kawata, Optics Letters **22** (2), 132 (1997).
22. M. Farsari, S. Huang, P. M. Birch, F. Clarte-Tournier, R. C. D. Young, D. Budgett, C. Bradfield, and C. R. Chatwin, optics letters **24** (8), 549 (1999).
23. S. Maruo and K. Ikuta, Applied Physics Letters **76** (19), 2656 (2000).
24. A. Bertsch, H. Lorenz, and P. Renaud, Sensors and Actuators: A **73**, 14 (1999).
25. T. Takagi and N. Nakajima, presented at the 7th IEEE Workshop on Micro Electro Mechanical Systems (MEMS'94), Oiso, Japan, 1994.
26. S. Ballandras, M. Calin, S. Zissi, A. Bertsch, J. C. André, and D. Hauden, Sensors and actuators A **62**, 741 (1997).
27. T. S. Ji, K. J. Vinoy, and V. K. Varadan, Smart Materials and Structures **10**, 1224 (2001).
28. S. Maruo, K. Ikuta, and T. Ninagawa, presented at the 14th IEEE International Conference on Micro Electro Mechanical Systems (MEMS2001), Interlaken, Switzerland, 2001.
29. K. Ikuta, T. Hasegawa, and T. Adachi, presented at the Transducers'01 Eurosensors XV Workshop, Munich, Germany, 2001.
30. K. Ikuta, presented at the International Microprocesses and Nanotechnology Conference, 2000.